THE WESTREX STEREODISK SYSTEM

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Abstract

The paper describes the Westrex StereoDisk Recorder which records two stereophonic channels in a single groove with a single stylus. The axes of the two recordings are at 90° to one another, each being at 45° with the horizontal plane of the record. By use of appropriate input circuits, the vertical-lateral type of stereo record may also be recorded. The recorder utilizes the electrodynamic feedback features of the Westrex lateral recorder. The design features of the recorder are described and the performance is discussed. Data on channel cross-talk, intermodulation distortion and frequency characteristics are given.

The design features and performance of the complementary StereoDisk Reproducer are described, including the desirability of maintaining the same vertical tracking angle in both recorder and reproducer. This reproducer employs dual d'Arsonval movements resulting in an exceptionally faithful reproduction.

Introduction

The current interest in stereophonic sound reproduction in the home has stimulated the development of the two-channel stereophonic disk system described in this paper. It is not generally recognized that considerable research was carried on in the 1930's on this type of stereo recording in which two channels are recorded in a single groove. For example, Blumlein of EMI in England was granted British patent No. 394,325 in 1933 on a two-channel stereophonic system. He disclosed the possible use of a vertical-lateral combination to produce a stereophonic effect. He also called attention to the 45-45 orthogonal system as an alternative method. At the Bell Telephone Laboratories, Keller and co-workers made stereophonic recordings as early as 1936 and Keller & Rafuse were granted U.S. Patent No. 2,114,471 in 1938. Blumlein and Keller built their experimental stereophonic recorders by linking existing lateral and vertical recording mechanisms. U.S. Patent No. 2,025,388 issued to Henning of BTL disclosed a reproducer capable of reproducing either vertical or lateral recordings. By using suitable output circuitry, Henning's reproducer has been successfully used to reproduce the Keller & Rafuse vertical-lateral recordings. The emphasis on defense work at the BTL in the late '30s, coupled with apathy on the part of commercial recording concerns, caused this development to be laid aside.

In developing the Westrex StereoDisk System, the authors were primarily interested in the development of a stereophonic system in which the two channels would give as nearly identical quality as was possible to achieve. In arriving at this conclusion, they were mindful of the work of Pierce & Hunt[1] in their comprehensive theoretical analysis of the lateral and vertical modes of disk recording in which they predicted the amount and type of distortion products obtained by tracing both lateral and vertical grooves. While this and other considerations enumerated below were important factors in support of the 45-45 orthogonal system, the symmetry of design it made possible for both recorder and reproducer was probably the determining factor. Further, the 45-45 system was capable of producing the vertical-lateral type of stereophonic disk if this method had been adopted by the industry.

General Description of 45-45 System

Having decided in favor of the 45-45 system, the next step was to evaluate design objectives in both recorder and reproducer in order to obtain a satisfactory stereophonic recording system for disks. A primary design objective in a dual channel stereophonic system is to obtain identical characteristics in the two channels. In the case of a disk recorder this means the stylus mounting mechanism must have equal compliance in all directions in a vertical plane normal to the recorded groove. If the recorder is to use moving coils, they should be identical and they should operate in identical amounts of magnetic flux. The coils should move the stylus through identical mechanisms. If this primary objective is not met, one channel must necessarily

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be inferior to the other in one or more respects requiring an unnecessary amount of effort to adjust and maintain the system for reliable commercial recording. It can be stated that consideration of this basic objective was an important factor in the adoption of the 45-45 method of recording. The final recorder design met the objective and also was capable of recording a vertical-lateral type of record while preserving the symmetry called for above.

It was decided that the new recorder should retain the feedback principle which has been an outstanding feature of both the Western Electric and Westrex recorders for the past 20 years and has been described previously[2]. This involved the mounting of a pickup coil on each of the drive assemblies in the recorder and including these coils in the feedback loops in the respective recording amplifiers. The design constants of the feedback circuit were of necessity a compromise of factors imposed by the design and performance requirements. The details of the feedback circuit are covered in the description of the recorder.

As a result of these considerations a feedback of approximately 27 db at the resonant frequency was employed. This held up the high-frequency response to at least 15 kc and the low-frequency response was brought up by the use of passive networks preceding the recording amplifiers. This arrangement of feedback maintained good stability over the significant range of audio frequencies, and, with the aid of the passive networks, essentially constant-velocity recording was provided over a frequency range from 30 to 15,000 cps, except for a very narrow dip of a few db in the vicinity of 11,000 cps. This characteristic is modified in commercial practice by inserting the RIAA or equivalent recording pre-equalization characteristic.

Two recording amplifiers, one for each channel, are required to operate the recorder. The circuits of the amplifier are shown in Figure 1 in block-schematic form since the details of design are not considered significant for this presentation. The recording circuit consists of a phase-inverter stage which drives a push-pull gain stage which in turn drives a push-pull, parallel power stage. The four-ohm output goes to one drive coil in the recorder. Adjustable low-frequency and high-frequency equalization is provided ahead of the phase-inverter stage. The output of the feedback coil in the recorder goes through a gain control to a gain stage. The output of this stage goes to the grid of the phase-inverter tube which also acts as a mixer. The output of the feedback coil also goes to a two-stage monitor amplifier which has a 600-ohm or 50-ohm output at a nominal monitor level of -15 dbm. The input network of the monitor amplifier provides the RIAA reproducing equalization.

Since the characteristic of the network used to provide constant-velocity recording is to some extent complementary to the RIAA pre-equalization recording characteristic, the two characteristics can be combined in a single equalizer with a considerable reduction of insertion loss.

The development of a reproducer was undertaken with the design objective of providing the highest quality of reproduction attainable. The three well-known basic principles of reproducer design were considered and the electrodynamic or rotating-coil type was selected as affording the best opportunity of meeting the design objective. Theoretical consideration indicated this type would provide appropriate compliance and low mass at the stylus compatible with basic requirements. It was indicated also that a satisfactory frequency response over the audio range with relatively low intermodulation and harmonic distortion might be expected. The details of design and performance of the reproducer are described elsewhere in this presentation.

Comparative Performance of V-L and 45-45

A comparison of the relative performance capability of the V-L and the 45-45 systems will indicate the reasons for the preference of the latter system. An analysis of the stereophonic groove cut with either the 45-45 or V-L system will show considerable similarities between the two types of recording. Thus, with the 45-45 system, both lateral and vertical modulated grooves will result depending on the phase relationships of the inputs. For random phase differences, a complex groove with both vertical and lateral components will be recorded. On the other hand, with the V-L system, vertical and lateral tracks will result only when one or the other microphone receives no signal. For the general case where sound is picked up by both microphones, the resultant groove will have both vertical and lateral components and will appear to be substantially the same as a groove cut with the 45-45 system.

In the V-L system, we might expect a preponderance of either vertical or lateral cut grooves while in the 45-45 we might expect a preponderance of 45^{o} modulations. Thus, the limitations on groove depth imposed by recording vertical components should be more severe than in the 45-45 system. In addition, by deliberately phasing the channels in the 45-45 system so that in-phase signals are recorded laterally, the limitations imposed by the vertical components are further reduced. Because of this situation, we would expect greater quality differences between the two channels in the V-L system due to the inherent but different tracing distortion components in the vertical and lateral grooves[1].

The symmetry of the 45-45 system is not only of importance in balancing the quality of the reproduction from the two grooves, but has certain other very important by-products. In the record changer, the vertical component of rumble is generally more pronounced than the horizontal component which would mean more audible rumble in one channel in the V-L system which is highly undesirable from a listening standpoint. In the 45-45 system, rumble should be identical in both channels and lower by about 3 db than in a strictly vertical channel. Another by-product favorable to the 45-45 system is the ease of balancing the reproducing channels in the home. It is only necessary to play a standard lateral record and adjust the channel gain for equal loudness.

In the 45-45 system each channel will have lateral and vertical components of the impressed modulation. Thus, it should be possible to reproduce either the lateral or vertical components of both channels with a standard lateral or vertical reproducer. Since vertical-type pickups are rarely encountered in home reproducing systems the lateral type of pickup only needs consideration. If this type of reproducer has good vertical compliance it should be able to reproduce satisfactorily the lateral components of both channels. In this sense the 45-45 system of stereophonic recording is compatible with lateral records. This cannot be said of the V-L system since the lateral component represents only one of the recording channels.

Design Details of Recorder

Figure 2 illustrates the basic design of the recorder. The magnetic gaps of the drive and feedback coils are arranged in a series parallel fashion. The magnetic flux is provided to the system by a single magnet made from Alnico V D.G. This arrangement of magnetic paths insures equal flux densities in the corresponding gaps. Each of the magnesium coil forms contains a drive and feedback coil as shown. The shaded areas between the magnetic gaps indicate copper slugs or shields which reduce inductive cross-talk from the drive coils to the feedback coils. This cross-talk must be minimized to utilize the advantages of negative feedback control of the drive coil motion. Figure 3 is a bottom view of the recorder. The individual coil assemblies are mounted on removable subassemblies, and are shown together with the other principal components in Figure 4. This permits their alignment in an assembly jig as self-contained units before installation. The coil forms have small terminals which are in turn connected through pigtails to corresponding stationary terminals on the assembly. This arrangement eliminates breakage of these vital connections to the coils due to vibration and it simplifies examination or service of these parts. The coil-supporting springs are made from beryllium copper and are "V" shaped to maintain the coils in proper alignment. The coils drive the stylus supporting member through separate linkages. These linkages consist of wires braced along their midsections to prevent excessive lateral compliance. The result is a relatively stiff driving system in a forward direction but with relatively high compliance in a lateral direction. This important relationship avoids the necessity of one coil bearing the mass of the other coil which would result if the coils were rigidly mounted on the stylus supporting member. Thus the mass of each driving system includes only its components and a negligible portion of the other driving system.

A tubular cantilever spring was chosen for the stylus supporting member because of the many advantages it offers. Its compliance as a cantilever is inherently the same in all directions in the desired plane, which is essential in order that the complex motion of the stylus may present uniform impedance in any direction in the vertical plane. This is particularly important at those portions of the frequency spectrum where the negative feedback voltage has little control of the stylus motion. Another feature of a tubular cantilever is its relatively low rotational compliance which reduces the tendency toward cross-talk from one channel to the other.

The damper shown on the stylus supporting member has little or no effect below 10 kc and very little effect above 10 kc on the actual recording. It is used mainly to smooth out several peaks and valleys in the monitor output reading. Therefore, the effects of temperature and other factors upon the damper in no way affect the system damping which is, of course, supplied by the feedback coil and the associated negative feedback loop in the recording amplifier.

The stylus has a tapered shank and is of the same type as those used in the 2B Recorder. The included angle of the stylus has only second-order effects on the recording. The same types of hot wire terminals are used to record with a heated stylus. Inasmuch as it appears impractical to hinge the stylus mounting mechanism of a recorder or reproducer exactly at the surface of the record, a vertical tracking error will be introduced unless very nearly the same angle is used in the recorder and reproducer. What is normally considered as "vertical" motion of the cutting stylus tip in the recorder is actually at an appreciable angle from a vertical line. It does not seem practical from the standpoint of construction of both recorder and reproducer for the situation to be otherwise. The angle for the recorder is nominally 23° in a direction such that with upward stylus motion, there is a component in the direction of travel of the record surface. This angle was determined by measurements on an actual stylus supporting member and a mock-up stylus, and was confirmed by calculations.

Description of 45-45 Groove

The geometry of the groove cut by the 45-45 recorder with a stylus having a cutting angle of 90° merits consideration in some detail. Figure 5 shows schematically cross-sections of the groove for four limiting conditions. The upper left section shows the type of groove which will be cut when signal is fed only to the left channel. The right-hand groove wall is a slant line of varying depth. The right edge of the groove at the record will be a smooth line without modulation. The left edge of the groove will vary in width in accordance with the signal. The upper right section of the figure depicts the opposite condition in which signal is fed only to the right channel. It will be noted that the conditions are just reversed. The lower left section shows the type of groove which is cut when identical signals are fed to the two channels and are in phase at the drive coils. Under this condition a vertical recording is obtained. The lower right section shows the condition when like signals are fed to the two channels but out of phase at the drive coils. Under this condition a lateral recording is made. Any combination of these four conditions in varying amplitudes may occur in recording stereophonic program material.

Figure 6 is a photomicrograph of grooves recorded first with a single frequency on one channel and then on the other. One side of each groove is essentially straight while the other varies in width in accordance with the lateral component of the signal. The vertical component of the signal is shown by the varying shading in the photograph. Figure 7 is a photomicrograph of grooves recorded using program material and a stereophonic pickup. Here again the lateral components are shown by the varying width of the grooves while the vertical components are represented by the varying shading in the photograph. Some of the vertical components in this picture represent frequencies of 12 kc or higher.

Figure 8 shows the maximum excursion of a groove which will be cut with a given maximum amplitude of modulation of the drive coils and with a specified minimum depth of groove. The specified minimum groove depth is D and the maximum modulation amplitude of either coil is A. Under these conditions the maximum horizontal excursion of groove will be $2D + 4\sqrt{2}\,A$ and the maximum depth of groove will be $D + 2\sqrt{2}\,A$.

The relative output level from a groove of specified maximum width recorded with the 45-45 system is a matter of considerable interest. Figure 9 shows a comparison of this type of groove with the conventional lateral groove. In each case the specified maximum groove excursion is $2D' + 2A'$. In the lateral groove the maximum amplitude of modulation is A which is equal to A'. In the 45-45 groove the amplitude of modulation in either channel is $\frac{A'}{\sqrt{2}}$. Accordingly the output of each of the 45-45 channels will be down 3 db with respect to the output of the lateral channel. For these conditions the playing time will be the same with the

45-45 system as for the standard lateral recording.

Performance of the Recorder

Fundamentally the performance of the recorder is based upon the use of moving coils with negative feedback control. The use of feedback to control resonance effects in vibratory systems was suggested first by Maxfield and Harrison[3]. The advantages of this type of transducer have often been described[2,4]. The moving coil offers a maximum of motional linearity and when combined with negative feedback it comprises a stable well damped system without resistive losses[5]. However, high efficiency must be obtained to provide the recorded levels used currently without excessive power losses which might destroy the coils with excessive heat. In order to achieve a practical physical size, the component parts of the magnetic circuits of the dual channel recorder must occupy a limited amount of space. To offset this condition two design features were incorporated.

(a) Minimum mass of the drive and feedback coils was used.

(b) The natural resonant period of the vibrating system was made relatively high.

Since it is unnecessary to generate sufficient feedback voltage to control the system throughout the entire audio band if equalization is used at one or both extremes, the physical size of the feedback coil and its operating flux may be reduced. Thus the mass of the vibrating system may be reduced and the relative amount of flux at the drive coil increased.

The natural frequency of the vibrating system is placed about one octave above the geometric mean frequency. This results in power economy in the high-frequency range where considerable power is normally required with the RIAA type of pre-equalization. The amount of feedback at resonance is approximately 27 db. This is sufficient to control the stylus throughout the range of frequencies where the mechanical impedance of the vibrating system is low. This is the range where variable cutting resistance presented at the stylus may cause non-linearity or wave distortion. Below this range the system is controlled by stiffness and is unaffected by cutting conditions. Throughout this range pre-equalization is required due to the loss of feedback control. Pre-equalization is not needed at high frequencies for a constant velocity recording characteristic.

The copper shields between the drive and feedback coils are intended to prevent inductive cross-talk between the drive coil and feedback coil. The effectiveness of these shields is at a minimum at about 200 cycles. Here the inductive cross-talk is -50 db relative to perfect coupling (i.e., the coils used in a perfect transformer). Since the feedback voltage generated by the velocity of the coil is already low, the inductive cross-talk and the feedback voltages are of the same order of magnitude. Therefore, the apparent feedback voltage reads proportionately higher at low frequencies than that represented by the recording and the feedback voltage cannot be used to calibrate low-frequency response without calibration data. This condition in no way contributes to instability and the system is inherently stable.

Single-frequency power measurements give little useful information from feedback recorders. In order to arrive at a practical evaluation of the power required by program material with an RIAA pre-equalizer, records were made at high levels from orchestral and vocal numbers. These were made from a single-channel source connected to the recorder and phased to produce lateral-type recording. The material was of the type containing high-level sounds which produce extreme velocities with RIAA pre-equalization. The highest peak velocity recorded was 19 cm per sec. as measured with the light-band method. The highest RMS value of current through one drive coil was 0.6 ampere. Therefore, the maximum power consumed by each 5.6-ohm coil was approximately 2 watts. The maximum groove swing was $\pm$ 1.65 mils which indicates this was a high-level microgroove recording. It is doubtful if this level will be reached in stereophonic recording on disks with the normal pre-equalization characteristic.

The complex stylus driving mechanism of the 3A Recorder must necessarily contain additional masses and compliances not found in single-channel recorders. The recorded product covers the extremes from vertical through 45° recording to lateral recording. Differences in characteristics are to be expected under these conditions. Lateral recording is most subject to the effects of lateral stylus rotation at high frequencies. Rotation produces dips in level as well as inter-channel cross-talk. Vertical recording appears to contain a minimum of rotational effects. At this point in the development of the recorder it is difficult to attempt a true evaluation of the amount of cross-talk and the frequency response of the recorder above 8 kc. It may be stated the average amount of modulation on the record when viewed optically appears higher at high frequencies up to 20 kc than at mid-range frequencies. The curve in Figure 10 is indicative of the response of a single 45° channel with a calibrated reproducer. The recording was made with a production recorder on a lacquer disk at 33-1/3 rpm and at an approximate diameter of 10 inches.

Reproducer Design

In order to facilitate the description of the reproducer, it is desirable to review in greater detail the design objectives which should be met. The mass of the moving assembly, including that of the coils, was made as small as possible, consistent with appropriate strength and adequate output level. Stylus compliance was next chosen of such a value as to give approximately equal reactances of the stylus against the record groove wall at 400 and 8000 cps, the frequencies which represent the approximate range of program material of equal velocity on the record. An additional requirement of the compliance was that the static deflection of the stylus due to the tracking force was to be large compared to the maximum deflection due to record groove vertical modulation. This was necessary to insure that the stylus would not lose contact with the record. High torsional stiffness at the stylus was an obvious necessity to restrict the stylus movement to one of translation and not of rotation. The stylus radius of 0.70 mil was chosen as a good compromise between a small radius for low distortion and good high-frequency response versus a large radius for long record life. Stylus force was chosen as the minimum value which would provide tracking at the highest recorded levels normally encountered.

The electrodynamic or rotating-coil movement was selected as affording the best means of meeting these requirements. Figure 11 is an illustration showing a simplified front and side view of the principal operating components of the reproducer. The two coils are self-supporting and are mounted on Mylar hinges with the coil axes at right angles to each other and at 45° with the horizontal. The lower edge of each coil is connected by means of a link to a beam in which the stylus is mounted. The beam (which actually is not subjected to bending or twisting) consists of a hollow tube whose outside diameter is .031" and whose length is approximately 0.15". The rear of the beam is anchored in a flat spring which prevents rotation and at the same time provides essentially equal compliance at the stylus in any direction in the vertical plane. Some mechanical damping is applied to each link close to the coil by introducing a block of viscous semi-solid material between each link and the reproducer housing. This reduces the height of a peak in the frequency response characteristic at about 11 kc and also reduces cross-talk between channels. The drag wire prevents longitudinal motion of the stylus. It will be observed that the beam is tilted downward at an angle of approximately 3° with respect to the horizontal when the stylus is free. However, when the stylus rests on a record the beam is in a horizontal plane and parallel with the record surface. The vertical angle of the reproducer stylus motion has been made to conform closely with the angle of the stylus motion in the recorder to avoid the introduction of harmonic distortion in the vertical component of the reproduced signal. The vertical angle of stylus motion was mentioned briefly in discussing the recorder and was stated to be nominally 23°. The reproducer has been designed to provide a corresponding angle of deviation from the vertical plane.

The angle difference between recorder and reproducer introduces tracking angle errors and is subject to the same mathematical analysis as tracking angle errors in lateral disk systems. Considerable literature has been published on this subject[6].

The applicable equation for a velocity-sensitive reproducer to a close approximation is:

$$D = \frac{0.2 \times A \times M}{R}$$

where

D = % 2nd harmonic distortion at 33-1/3 rpm
A = Tracking-angle error in degrees
M = Modulation velocity (cm/sec. peak)
R = Distance of groove from record center (inches)

Figure 12 is a family of curves obtained by the use of this equation which shows the amount of second-harmonic distortion for various amounts of tracking angle error. The curves are for grooves cut at constant velocity and at different distances from the record center. In Figure 13 the second-harmonic distortion is shown for various groove radii for a constant tracking angle error and at two recorded velocities. In both cases the amount of distortion is reduced to 63 per cent of the values shown, by the average 4-db-per-octave slope in the RIAA reproducing characteristic.

Referring to Figure 11, the magnetic path consists of a center pole piece, two magnet pole pieces and a magnet. The latter is not shown. One edge of each coil is disposed in one of the gaps between the center pole piece and the magnet pole pieces. The polarity of the coil leads is so arranged that a laterally modulated groove will produce signals which are in phase in the output circuits.

Figure 14 is an outside view of the reproducer. It is entirely enclosed except for the small clearance hole for the diamond stylus and it mounts in a standard reproducer arm. It tracks properly with six grams of stylus force. The stylus compliance is nominally 2.6×10^{-6} cm/dyne and the dynamic mass is 3.0 milligrams. To avoid the difficulties involved in winding the moving coils with a large number of turns of extremely fine wire, a wire size has been chosen that results in a low output impedance of 2.4 ohms and a correspondingly low output voltage of 2 millivolts rms per channel for 10-cm-per-second peak velocity. A pair of transformers is therefore required for good signal-to-noise ratio.

A typical frequency response of one channel of the reproducer is shown in Figure 15. This characteristic was obtained by reproduction from an optically calibrated pressing containing single-channel test frequencies recorded at 45°. The slight rise at the low-frequency end of the curve is the result of the resonance of the arm mass with the stylus compliance and it will vary somewhat with the mass of the arm employed.

Tracing Distortion

Recordings made with the 45-45 method may vary all the way from single-channel 45° records to all vertical or all lateral types. Therefore, a single 45° channel may receive the same information from any of these types. However, tracing distortion may be expected to exhibit different characteristics in all three cases due to the differences in tracing distortion between vertical and lateral or combination recordings thereof.

The following distortion measurements were made from records recorded under all three conditions. The input level per channel was the same in all cases. The recorded velocity was 2.5 cm per sec. (peak) per channel. This resulted in an amplitude variation of $\pm$ 0.55 thousandths of an inch at the 400 cycle fundamental frequency.

Figure 16 shows the total harmonic distortion as measured through the usual high pass filter measuring device.

Figure 17 shows the intermodulation distortion measured with the RA-1258 Intermodulation Generator and the RA-1257 Intermodulation Analyzer.

The system of stereophonic recording on disk described in this paper appears to give highly satisfactory two-channel stereophonic reproduction. The cross-talk of the over-all system shown in the lower curve in Figure 15 appears to be entirely satisfactory for stereophonic listening and the frequency response is entirely adequate for high-fidelity reproduction in the home. Experience to date indicates little if any added problems in producing pressings with a low noise level. The system has been demonstrated widely to representatives of the disk recording studios and reproducing equipment industries both here and in Europe. A limited number of 3A Recorders has been placed in the hands of several recording companies and experimental disk recordings have been made available by some of them. Interest shown by industry and the public in the demonstration of the 45-45 StereoDisk System would appear to confirm the soundness of this approach to the application of stereophonic recording principles to the field of disk recording.

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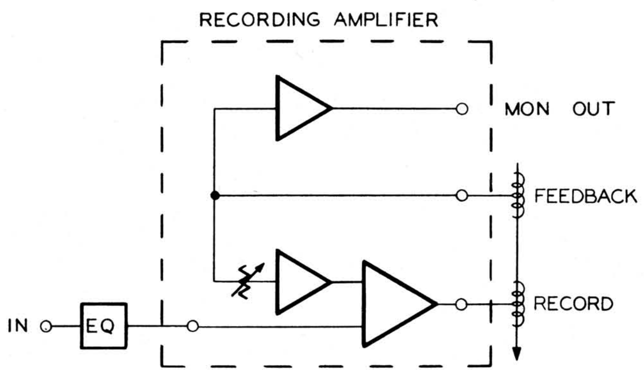

Fig. 1 Block schematic of recording amplifier.

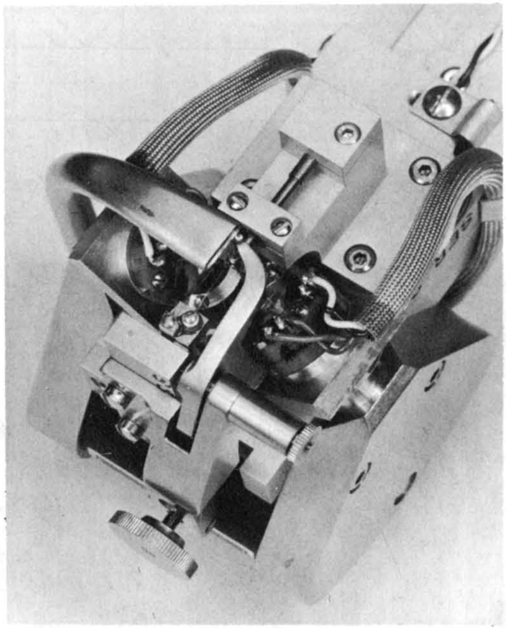

Fig. 3 Bottom view of 3A StereoDisk recorder.

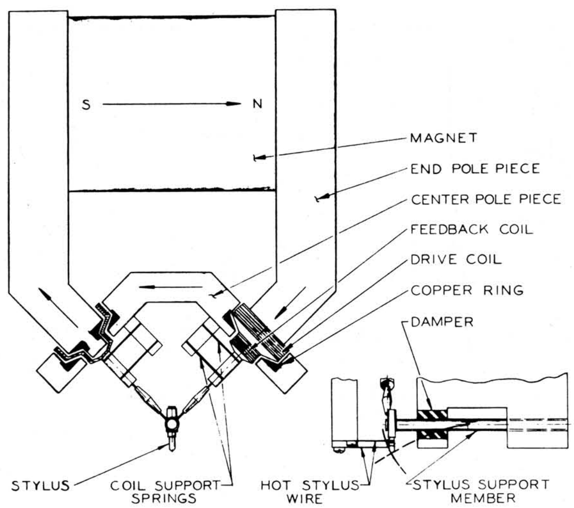

Fig. 2 Simplified recorder illustration.

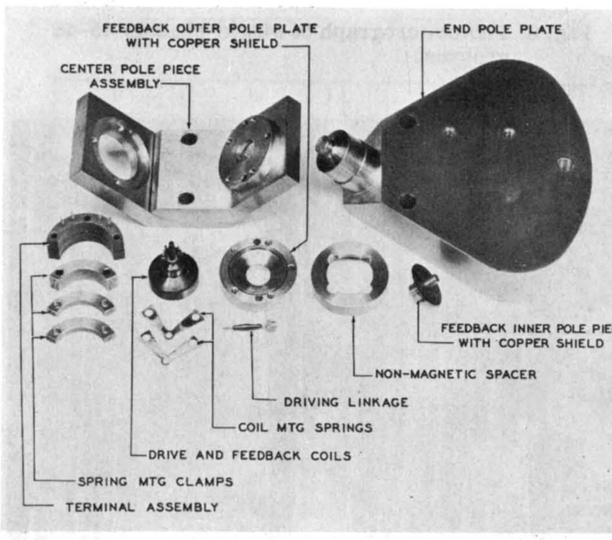

Fig. 4 View of significant parts of recorder.

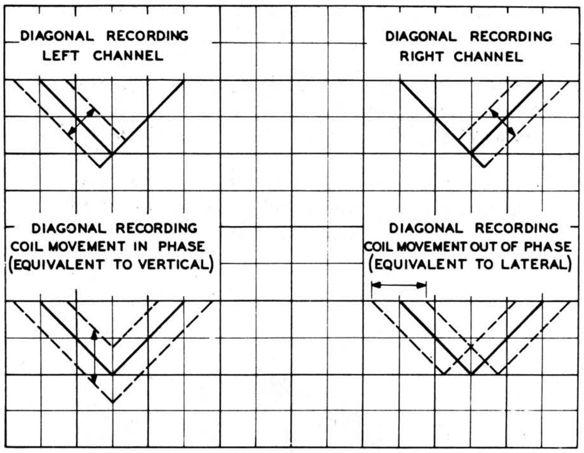

Fig. 5 Cross section of 45-45 grooves for four limiting conditions.

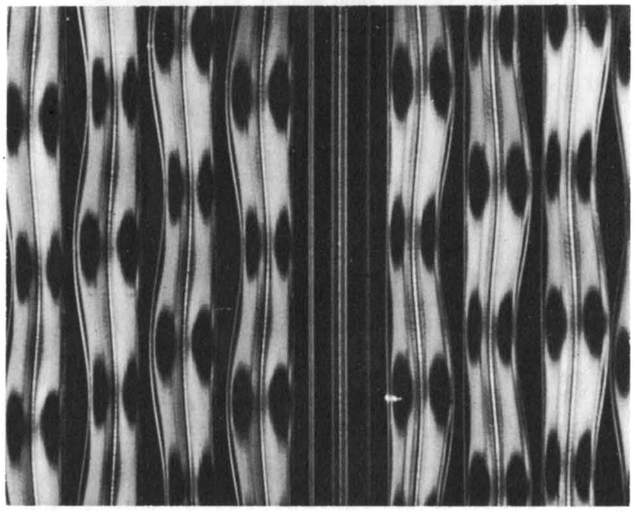

Fig. 6 Photomicrograph of single-channel 45-45 grooves.

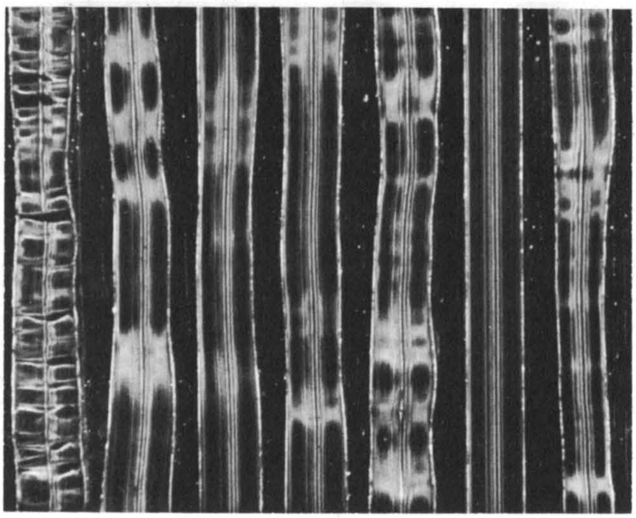

Fig. 7 Photomicrograph of 45-45 grooves with stereophonic program material.

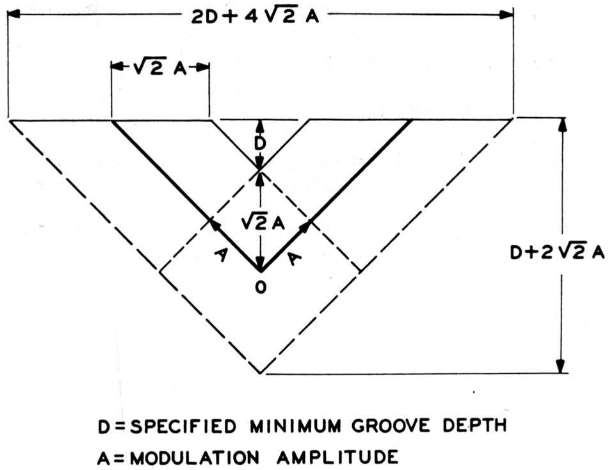

Fig. 8 Cross section of 45-45 groove for maximum groove excursion.

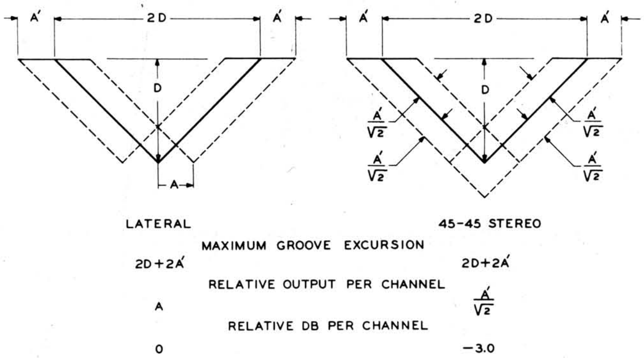

Fig. 9 Comparison of 45-45 with standard lateral groove.

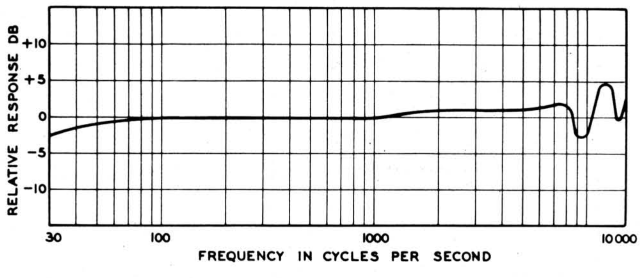

Fig. 10 Typical recorded frequency characteristic.

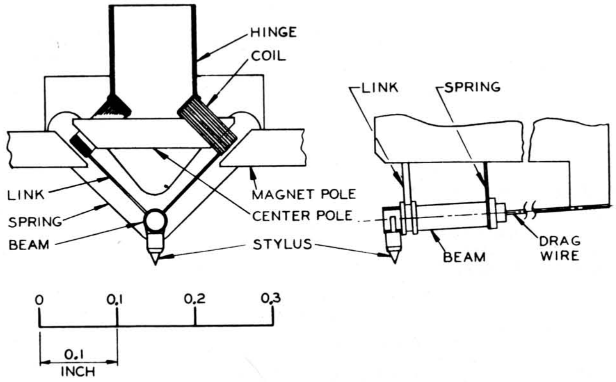

Fig. 11 Simplified reproducer illustration.

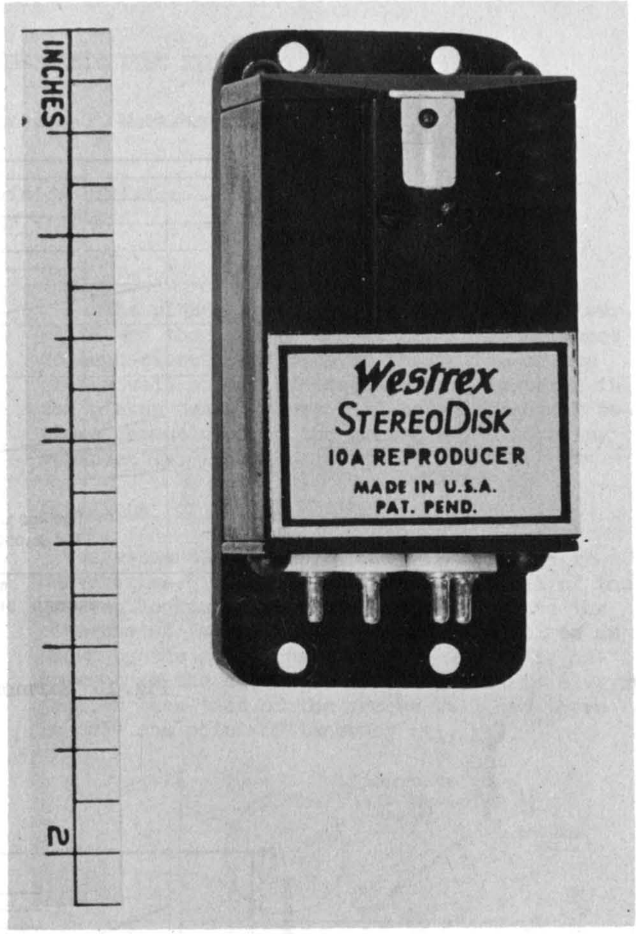

Fig. 14 View of 10A StereoDisk reproducer.

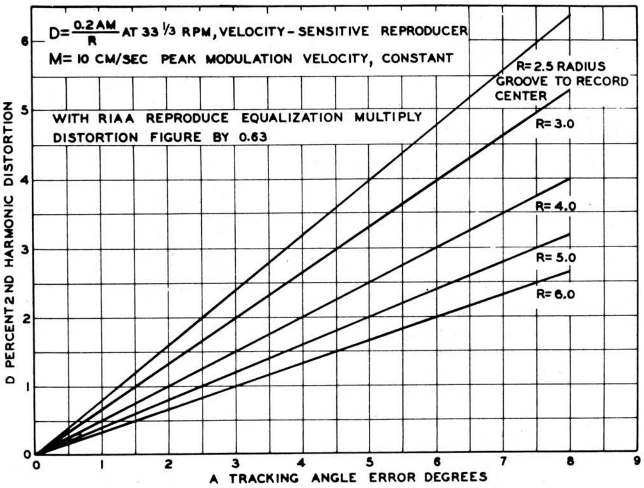

Fig. 12 Distortion vs. tracking-angle error.

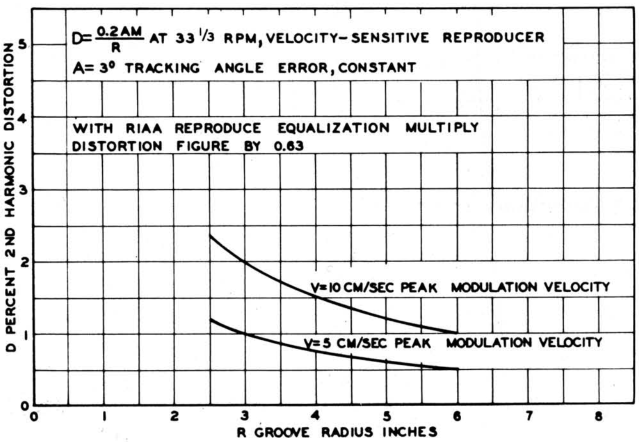

Fig. 13 Tracking-angle distortion vs. groove radius and recorded velocity.

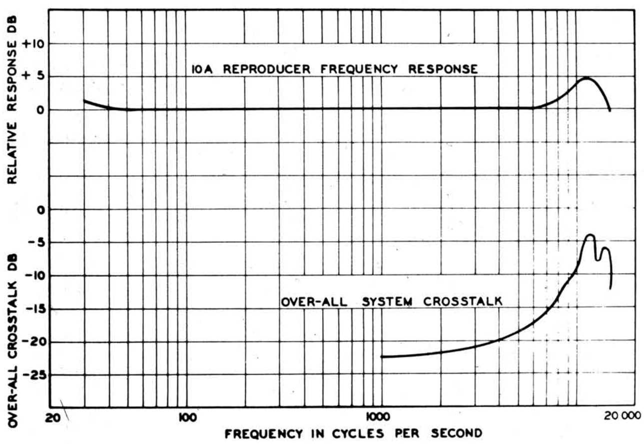

Fig. 15 Reproducer frequency characteristic and system cross-talk.

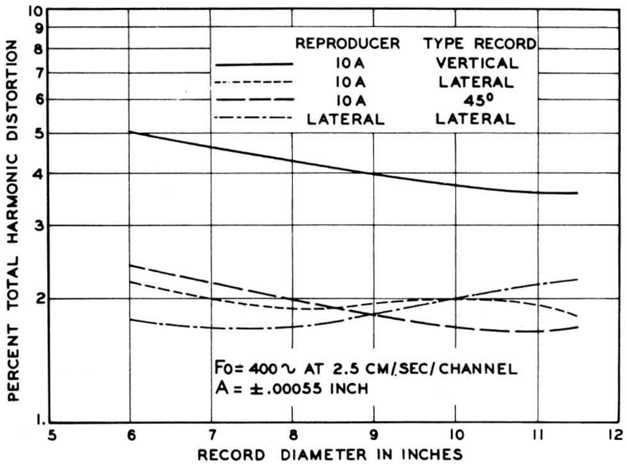

Fig. 16 Harmonic distortion curves.

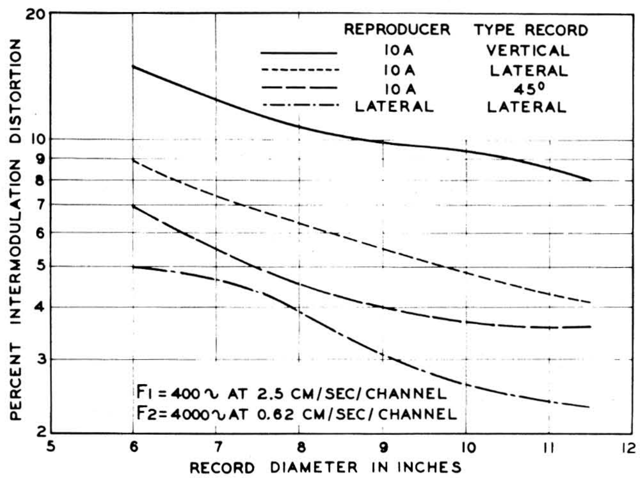

Fig. 17 Intermodulation distortion curves.